APPENDIX IV

MEASUREMENTS OF LIP PRESSURE EXERTED ON A CIGARETTE DURING NORMAL SMOKING

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ABSTRACT

Measurements were made of the pressure exerted by human lips on the filter of a cigarette during normal smoking conditions using a small, fluid-filled bulb attached to a low-compliance pressure transducer. In two series of measurements, the mean lip pressure and standard error were 34.2 (± 3.0) and 35.2 (± 2.9) torr, respectively. These pressures compared favorably with those applied by the Cambridge holder (used in the standard FTC testing procedure), but were much lower than the pressures exerted by two different holders (Filtrona and Borgwaldt) both of which are constructed from a rigid cylindrical housing with a segment of latex tube mounted inside. Pressures measured by these two holders were in close agreement with the pressures predicted by a nonlinear theoretical model for the distention of latex rubber tubes.

INTRODUCTION

Although factors relating to smoking behavior have been the subject of considerable study, interactions between the smoker's lips and the cigarette filter have received relatively little attention. This is no doubt due to the fact that, for most brands of cigarette, the lip-filter interaction has little effect on what the smoker receives in the way of tar and nicotine. While this has generally been assumed in the past, the lips may actually play a significant role in all cigarettes that are ventilated to reduce the levels of tar and nicotine in the smoke. If the lips impair the normal flow of ventilation air, the delivery of these substances could be considerably increased from that indicated by the accepted testing procedures. Obviously, if either the lips or the fingers of the smoker cover the ventilation holes, then the smoker will, in effect, be smoking a much stronger cigarette. Finger blockage has, in fact, been observed in as many as 40% of all ventilated cigarette smokers according to a recent study [Kozlowski (1982)].

Recently, a new type of filter has been introduced that could be susceptible to a somewhat different type of 'sabotage'. This filter also has ventilation perforations at approximately the same location on the filter as other conventional filters, but these perforations directly communicate only with four small grooves that run beneath the filter paper to the end of the filter. If these grooves were to become collapsed due to pressures exerted by the lips during smoking,

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then once again the smoker would receive more smoke than would a testing machine and the machine figures would, in fact, be misleading to the consumer. This presumes, of course, that the holder used during testing does not compromise the flow of ventilation air in any way due, for example, to pressures that are unrealistically high. Clearly, the pressures exerted by human lips as compared to those applied to the filter by the various filter holders used in cigarette testing, becomes an important factor.

I have conducted a series of tests under conditions simulating normal smoking in which the contact stress acting between the smoker's lips and the cigarette filter has been measured. The pressures exerted by three different types of cigarette holder have also been measured and compared to the measurement of lip pressure. These measurements will be presented and their import for the ventilation reaching the smoker will be discussed.

Since measurements of this type have not been made in the past, it was necessary to develop a new measurement technique for this purpose. The technique devised for these tests draws upon methods that have been used to measure contact stress in other situations, but differs both in the size of the sensing element and the sensitivity required.

Various methods have been employed in the past to measure the contact stress acting between two solid surfaces. These methods generally measure the force applied to a known surface area by way of the deflection of a diaphragm or the change in electrical properties

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of a piezoelectric or piezoresistive device. Although these methods are reliable and accurate in most applications, they fail in this situation either because they lack the necessary sensitivity or because they cannot be sufficiently miniaturized to ensure that the act of measurement will not significantly influence the pressures we wish to determine. To ensure reliable measurement of lip pressure, a device is required which is small compared to the cigarette diameter and which conforms to the smoker's lips when contact is made. The device must be sensitive and capable of measuring pressures, accurately, down to 10 or 20 torr (1 torr = 1 mm Hg).

Somewhat similar measurements have been made inside the mouth. In these, the purpose has been to determine the pressures exerted between the lips and the teeth or the tongue and teeth. Intra-oral pressures have been measured both by a technique similar to that employed in these tests, and by using a sensitive strain gage mounted on the tooth surface or in a small plastic housing. In such tests, pressures in the range of 20 to 150 torr have been observed in normal activities such as speaking and swallowing [Proffit (1975)].

EXPERIMENTAL METHODS

Measurement Apparatus. In order to satisfy the stringent requirements stated above, a miniature pressure sensing element was developed. This miniature probe consists of a thin-walled, latex rubber bulb, nearly spherical in shape (dia. ≈ 1.5 mm) with a narrow throat to allow attachment to a segment of hypodermic needle tubing (L = 1 cm, I.D. = 0.01 cm). The needle tubing is connected to a teflon catheter (L - 50 cm, I.D. = 0.05 cm) that leads to a low compliance pressure transducer. The entire system (bulb to transducer) is filled with water to eliminate the compliance due to fluid compressibility and, therefore, maximize the usable pressure range of the device.

The bulb was mounted on the cigarette filter in one of two ways. In one set of experiments (Series I) the bulb was attached directly to a small exposed segment of the cellulose filter material at a distance of 7 mm from the tip of the filter using a fast-acting contact adhesive. In the other set (Series II) the bulb was first mounted onto a 1 cm long segment of thin-walled latex tube (nominal I.D. = 0.79 cm) which could be slipped over the end of the filter to the desired position. The latter modification was adopted merely to facilitate the mounting of the probe.

The assembled apparatus is shown in Figure 1. When mounted in the fashion shown, a smoker's lips or filter holder would press on the sensing probe causing the internal fluid pressure to increase. This is immediately sensed by the pressure transducer and can be displayed on an oscilliscope screen.

Due to the properties of the bulb and to the distribution of stresses on the bulb, the recorded pressure (P_{rec}), in general, differs from the applied pressure (P_{app}). To illustrate, consider a general functional relationship between the volume of the sensing bulb (V_{bulb}), the pressure difference acting across the bulb ($P_{app}-P_{rec}$), and the distribution of pressure acting on the external surface of the bulb [$D(\vec{r}_s)$],

$$V_{bulb} = V_{bulb}[P_{app}-P_{rec}, D(\vec{r}_s) \qquad (1)$$

where $\vec{r}_s$ denotes position on bulb surface]

Because the volume of incompressible fluid within the measurement system is constant, changes in bulb volume (ΔV_{bulb}) and changes in transducer and tubing volume (ΔV_{trans}), must be of equal magnitude but of opposite sign. Therefore, we can write:

$$V_{bulb} = V_{bulb,i} + \Delta V_{bulb} = V_{bulb,i} - \Delta V_{trans} \qquad (2)$$

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We further note that ΔV_{trans} is a function only of the internal pressure and can therefore state:

$$\Delta V_{trans} = \Delta V_{trans}(P_{rec}) \quad (3)$$

Combining (1)-(3), we can deduce the following functional relationship:

$$P_{app} = h[P_{rec}, D(\vec{r}_s)] \quad (4)$$

Therefore, to the extent that the distribution of external pressure is either relatively constant or unimportant, P_{rec} will be directly related to P_{app}.

Since the exact form of the function h is not known, a calibration apparatus was developed and used with each individual test. The device (Figure 2) was designed so as to mimic as closely as possible the distribution of pressure produced by the lips, thus maintaining $D(\vec{r}_s)$ roughly constant. The calibration device consists of two rigid Plexiglas plates, each machined to accept a cigarette, and a 10 cm length of thin-walled latex rubber tubing. When assembled, the latex tube is positioned directly over the sensing bulb and any pressure applied inside the tube is directly exerted on the sensing bulb. A calibration curve was obtained by inflating the latex tube to approximately 5 or 6 levels of pressure within the range of interest. The relationship was plotted as E_{rec} vs. P_{app} (E_{rec} is the output voltage of the transducer associated with P_{rec}) as in the sample curve given in Figure 3.

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<u>Protocol for Lip Pressure Measurements</u>. In preparation for an experiment, the sensing probe was mounted onto a cigarette in one of the two ways described above. The smoking panelist was then brought into the room and was seated at a table on which the instrumented cigarette had been placed. Each panelist was asked to smoke in a normal fashion and at a normal pace, taking care to position the small sensing probe squarely against their lip. For each test, we obtained approximately ten pressure measurements: five with the bulb positioned against the lower lip and five with the bulb positioned against the upper lip. The pressure excursions during each puff were monitored using an oscilliscope and the <u>maximum</u> deflection for each puff was recorded.

During the course of measurement, it was occasionally necessary to guide the panelist with regard to bulb position. Observing the pressure on the oscilliscope, it was immediately evident when the panelist's lip had missed the bulb. All cases in which the bulb was missed were ignored.

Each cigarette was calibrated using the procedure described above either prior to or following the test. In several cases the calibration was performed both before and after the lip pressure measurements to ensure consistency of the calibration relationship.

In the two series of tests, usable data were obtained on 12 and 18 subjects, respectively. Three sets of data were not used due to one of two problems -- either the bulb ruptured during the test, or the teflon catheter came too close to the burning ash and melted. All the results are summarized in Table 1.

Filter-Holder Measurements. The measurements of pressure exerted on the three filter holders were all conducted with the same instrumented cigarette,+ calibrated in the manner described above. In each case, several pressures were recorded at the position of peak pressure within the holder and are summarized in Table 2. The three holders tested are sketched in Figure 4. They are:

1) Cambridge. This holder, the FTC standard, is comprised of a rigid plastic holder on which a latex rubber sheet can be mounted. The latex sheet used in this test was the industry standard, 0.20-0.23 mm thick with a 3 mm dia. hole. When stretched onto the holder, the hole diameter increases to 3.9 mm.

2) Borgwaldt. This holder is made from a rigid, cylindrical housing with a latex tube slipped inside and stretched over the two ends. The standard latex sleeve used in our tests had dimensions: O.D. = 7 mm, wall thickness = 0.36-0.43 mm.

3) Filtrona. This holder consists of a cylindrical housing with a latex sleeve inside, mounted on the two ends. It differs from the Borgwaldt mainly in terms of the tube dimensions: (O.D. = 6 mm, wall thickness = 0.38 mm).

+ The diameter of a cigarette filter is 8 mm.

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DISCUSSION OF RESULTS

Lip pressure measurements. The objective of this study was to measure the pressures exerted by human lips during normal smoking and to compare these pressures to those produced by various types of cigarette holders used for testing purposes. The values of lip pressure presented in Table 1 are seen to fall in a wide range with a mean value of 34 torr. This was lower than any of the filter holders tested, but was closest to the pressures produced by the Cambridge holder.

The scatter in the data reported in Table 1 can be attributed to a variety of factors. First, there are obvious differences in jaw structure, muscle tone and smoking behavior between individuals. Even the same individual will exhibit a wide degree of variability from one draw to the next. In this regard, it is useful to look at a comparison between the overall mean pressure and the maximum pressure for each subject (Table 1). Typically, the maximum pressure was about twice as high as the overall mean. Five subjects, however, exhibited values of P_{max} greater than four times as high as the mean. We suspect that this was due to the panelists' teeth coming into contact with the sensing bulb. Another source of variability is in the positioning of the bulb between the panelists' lips. Clearly, the contact stress acting between the filter and lips will be distributed non-uniformly both along the axis of the cigarette and around the circumference. By instructing the panelist to place the bulb squarely

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against either the upper or lower lip, we attempted to obtain a measurement near the maximal point of this distribution. Due largely to the considerable variability of insertion depth from smoker to smoker, however, this was often difficult to accomplish. This was most vividly demonstrated by the total absence of signal when the panelist's lips missed the probe altogether. Therefore, these measurements must be viewed as approximate peak pressures and that, based on the variability of our measurements, the actual peak pressure during any particular puff may typically be two to three times as large as the mean value given in Table 1.

The pressures we observed are in approximate agreement with measurements of pressure in a region lingual to the maxillary molars during the act of speaking, for example. Using measurement probes mounted in plastic, Proffit (1975) found contact stresses to lie in the range of 10 to 60 torr for teenage caucasian subjects.

All the measurements reported thus far pertain to the maximum pressure excursion for each individual draw on the cigarette. The peak is recorded during a pressure history that typically has the appearance of the trace shown in Figure 5. Although deflections in this trace are not linearly related to lip pressure, we can still draw broad inferences from its general shape. Characteristically, the signal would rapidly deflect and reach an early maximum as the smoker placed the cigarette into his or her mouth and began to draw. Sometimes we observed a single plateau during this rising phase corresponding to a short pause between cigarette insertion and the onset of draw. The pressure would fall more or less rapidly as the

draw progressed, level off at the end of the draw, and then fall to zero as the cigarette was removed from the mouth. From traces like these, we are able to conclude that the pressure maximum is of very short duration and that the time-mean pressure during the draw is on the order of half the peak value.

Filter-holders. The three filter-holders were found to exhibit grossly different characteristics both in terms of the values of peak contact stress, and also in the distribution of that stress upon the filter.

Of the three filter-holders tested, only the Cambridge holder came close to exerting pressures comparable to those produced by the lips. The pressures exerted by the Borgwaldt and Filtrona holders were about 4 and 15 times larger than lip pressure, respectively. The differences between these two can be attributed entirely to the proportion and dimensions of the tubing used as demonstrated in the Appendix.

The pressures are not only lower with the Cambridge holder, but also act over a smaller surface area as compared to either the Borgwaldt or Filtrona holders. The region of contact in all cases is symmetric around the filter circumference but ranges in length from about 3 mm in the Cambridge to about 10 mm in the Borgwaldt and Filtrona.

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These measurements of filter-holder pressure provide us with an additional check on the validity of our measurement technique. By the analysis described in the Appendix, it is possible to predict the approximate pressure exerted by either of the tube-in-cylinder holders (Borgwaldt or Filtrona). Accounting for an axial strain imposed during the mounting procedure of about 15% and for the effects of finite deformation and wall thickness, we come up with predicted pressures of around 520 torr for the Filtrona and 150 torr for the Borgwaldt holder (see Figure 6). These are in close agreement with the measurements reported in Table 2, suggesting that our measurements are, indeed, correct and accurate.

SUMMARY

Using a pressure probe developed specifically for the measurement of lip pressure and calibrated using a device which was designed to simulate the action of human lips, the pressures exerted by the lips of a smoker and by various types of cigarette holder have been measured. I found that the contact stress exerted between the lips of a smoker and the cigarette filter were comparable to those exerted within the mouth as measured by other techniques, but were generally lower than those produced by the various types of cigarette filter-holders used for testing purposes. Only the Cambridge holder (currently recommended by the Federal Trade Commission) produces pressures that are close to lip pressures.

APPENDIX -- PREDICTION OF FILTER-HOLDER PRESSURES

The measurement of filter-holder pressure proved to be useful, not only for comparison to lip-pressure but also as an independent means of calibration. Because the geometry of the two latex tube holders (Filtrona and Borgwaldt) is symmetric and relatively simple, the pressure they exert on a filter of known diameter can be predicted with reasonable accuracy.

The elastic tubes used in these two holders are subjected to both axial and circumferential strain denoted by ε_x and ε_θ, respectively. If the tube wall is assumed to behave as a homogeneous and isotropic thin-walled membrane, then these strains are related to the circumferential tension through [Tomoshenko and Woinowsky-Krieger (1969)]:

$$T = Eh(\varepsilon_\theta + \sigma\varepsilon_x)/(1 - \sigma^2) \qquad \text{A-1}$$

where E is the Young's modulus of the material, σ is Poisson's ratio and h is the tube wall thickness. The axial stress satisfies:

$$Q = Eh\,(\varepsilon_x + \sigma\varepsilon_\theta)/(1 - \sigma^2) \qquad \text{A-2}$$

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The pressure difference across the membrane is related to the membrane tension and local radius of curvature in two mutually perpendicular planes and is given by:

$$\Delta P = P_{int} - P_{ext} = T/R_\theta - Q/R_x \qquad \text{A-3}$$

where, R_θ and R_x are the radii of curvature of the surface in a cross-sectional and axial plane, respectively.

When the tube is mounted but before a cigarette is inserted into the holder, $P_{int} = P_{ext}$ and

$$T/R_\theta = Q/R_x$$

When the cigarette is in place, $R_x = \infty$ and

$$T = R_\theta \Delta P = Eh\,(\varepsilon_\theta + \sigma\varepsilon_x)/(1 - \sigma^2) \qquad \text{A-4}$$

Moreover, since the volume of tube wall remains constant:

$$hRL = h_o R_o L_o \qquad \text{A-5}$$

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where h_o, R_o, and L_o are the thickness, radius and length of the unstressed tube. Changes in radius and length are related to the circumferential and axial strain according to:

$$\varepsilon_\theta = (R - R_o)/R_o$$

$$\varepsilon_x = (L - L_o)/L_o$$

These expressions can be combined with (A-5) to yield:

$$h = h_o(\varepsilon_\theta + 1)\,(\varepsilon_x + 1)$$

Substituting into A-4 we obtain:

$$\Delta P = E h_o R_o (1 + \varepsilon_x)[((R - R_o)/R_o) + \sigma\varepsilon_x]/[R^2(1 - \sigma^2)] \qquad \text{A-6}$$

Of the parameters on the right in A-6 only ε_x is unknown. Rough estimates suggest that it is roughly equal to 0.15 for both filter-holders tested. Plotting ΔP as a function of axial strain, we obtain Figure 6.

The above analysis assumes both that the wall is very thin and that the stress-strain behavior of latex rubber is linear. This is,

however, only an approximation which is decreasingly valid for large strains. An analysis that relaxes both of these constraints has been performed by Taylor and Gerrard (1977) for the case of zero axial strain. Their result can be written:

$$\Delta P = \frac{2}{3}\frac{E h_o}{D_o}\left(1 - \frac{R_o^4}{R^4}\right)\frac{(1 + h_o/2R_o)}{(1 + h_o/R_o)^2} \qquad \text{A-7}$$

The value of ΔP computed by this equation is also shown in Figure 6. If we assume, without proof, that changes in axial strain affect ΔP similarly for both cases, we obtain the approximate relationships indicated by the dash-dot lines in the figure.

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Timoshenko, S. and Woinowsky-Krieger, S., Theory of Plates and Shells, Eng. Soc. Monograph, 1969.

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TABLE 1. DATA SUMMARY: LIP PRESSURE MEASUREMENTS

SERIES I

Subject	Upper Lip (P_u) (Torr)	Bottom Lip (P_b) (Torr)	Overall ($\bar{P}$) (Torr)	Lighting (P_L) (Torr)	$\frac{P_{max}}{\bar{P}}$ (Torr)
1	(no useful data -- see text)				
2	87	110	98.5	100	1.7
3	40	16	28	53	1.9
4	2.5	2.9	2.7	13	4.8
5	60	71	65	100	1.5
6	53	6.0	29	11.3	2.7
7	57	3.9	30	10(a)	8.5
8	88	4.4	46	3.4(a)	5.3
9A	10 > 7.5	16 > 13.2	13 > 10.4	8.8(a) > 13.2	3.1
9B	5.1	10.4	7.8	17.5(a)	1.5
10	16.7	15.5	16.1	12.5(a)	1.6
11	51.3	3.3	27.3	3.8(a)	4.0
12	18	25	21.5	7.5(a)	2.3
Average (s.d.)	43.7 (29.7)	24.7 (34.4)	34.2 (32.9)	55 (44.0)/8.4 (4.2) 29.8 (37.2)[b]	

(a) Lighting with bulb on lower lip.
(b) Upper lip/Lower lip. Overall average directly below.

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TABLE 1. DATA SUMMARY: LIP PRESSURE MEASUREMENTS

SERIES II

Subject	Upper Lip (P_u) (Torr)	Bottom Lip (P_b) (Torr)	Overall ($\bar{P}$) (Torr)	Lighting (P_L) (Torr)	$\frac{P_{max}}{\bar{P}}$ (Torr)
1	7.9	18.8	14.0	(a)	2.1
2	(calibration error)				
3	7.0	6.7	6.8	(a)	1.5
4	59.5	4.8	32.1	6.4 (b)	6.3
5	4.4	3.5	4.0	2.54 (b)	1.6
6	27.5	2.1	14.8	(a)	3.4
7	124	144	133	135 (c)	1.3
8	10.7	37.5	22.6	(a)	2.6
9	9.5	2.6	5.7	1.0 (b)	1.6
10	14.9	6.7	9.7	4.1 (b)	2.1
11	51.8	1.5	26.6	(a)	3.7
12	(bulb rupture)				
13	(bulb rupture)				
14	54.0	22.4	35.1	20.3 (b)	2.3
15	63.5	115	82.9	57.1 (c)	2.1
16	57.5	31.5	44.6	(a)	2.8
17	138	31.6	80.5	7.6 (b)	2.2
18	97.4	27.9	54.0	5.1 (b)	1.9
19	7.0	6.8	6.9	12.7 (c)	1.8
Average ± s.d.	45.8 ± 43.1	29.0 ± 41.4	35.8 ± 36.1	25.1 ± 41.9	2.79 ± 1.68

(a) Bulb not against lip.
(b) Lighting with bulb against bottom lip.
(c) Lighting with bulb against upper lip.

TABLE 2

FILTER HOLDER PRESSURE MEASUREMENTS

Filter Holder	Contact Pressure (Torr)	No. of Observation
Cambridge	47	2
Borgwaldt	118	3
Filtrona	500	15

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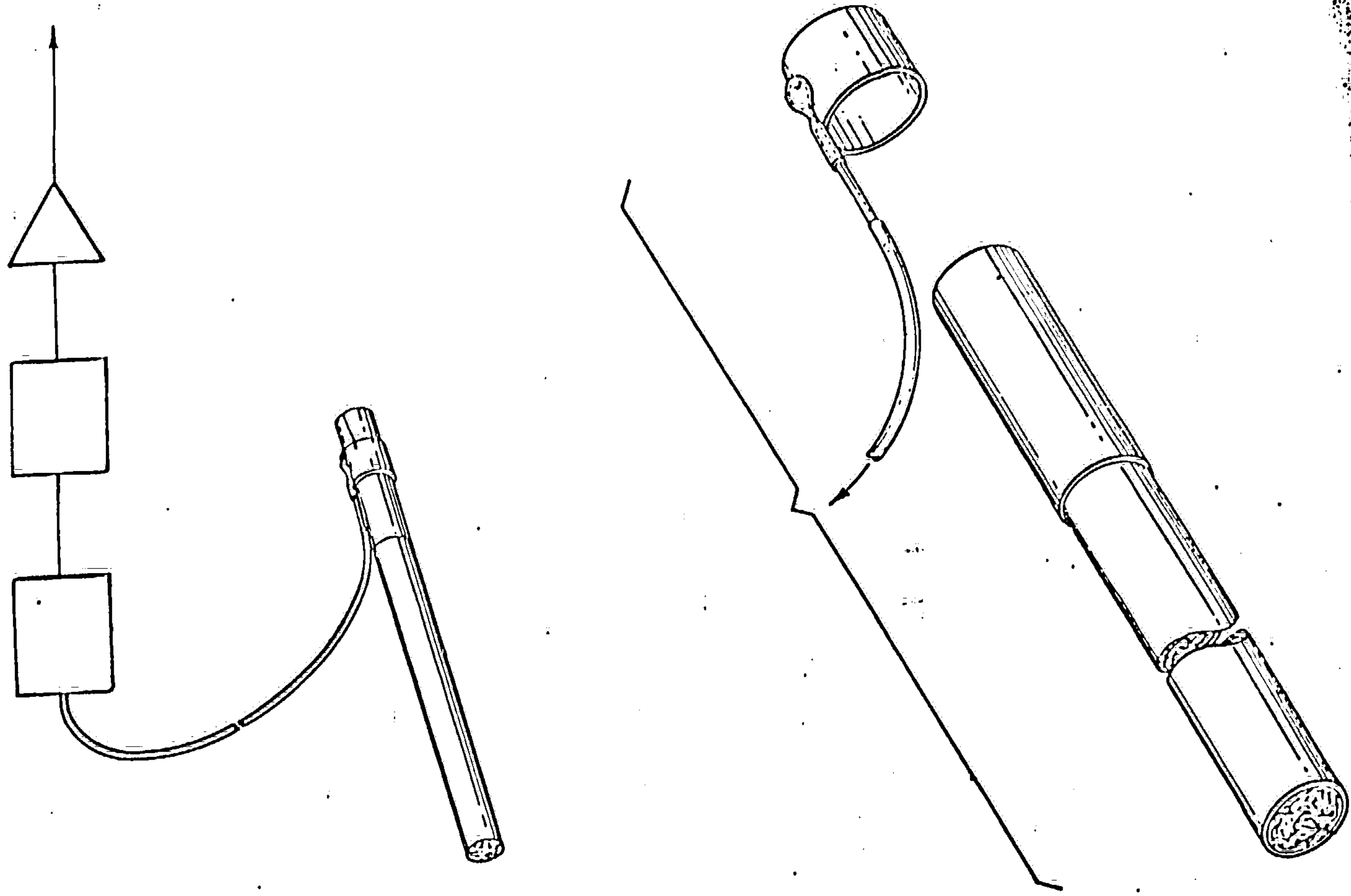
FIG. 1



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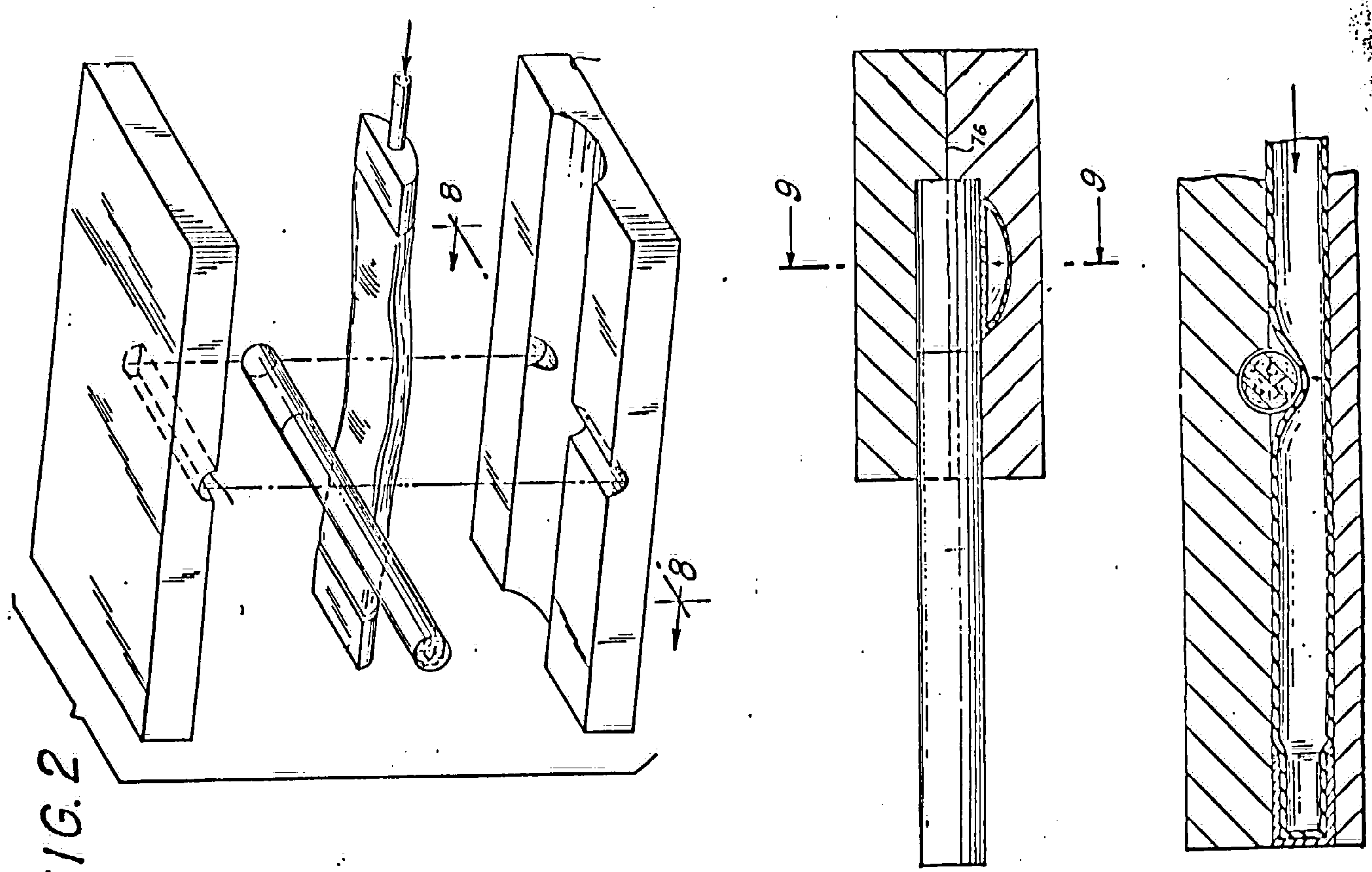

FIG. 2

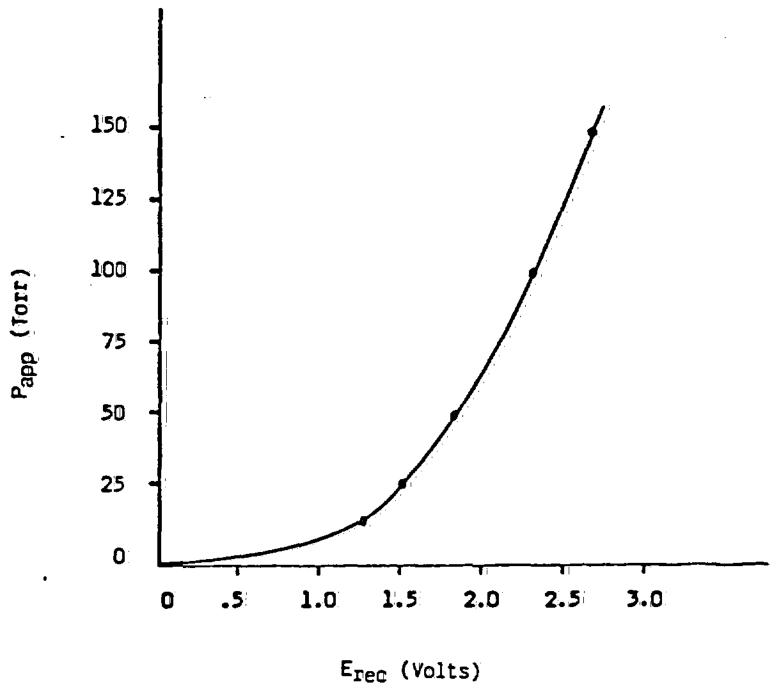

Figure 3. Sample Calibration Curve

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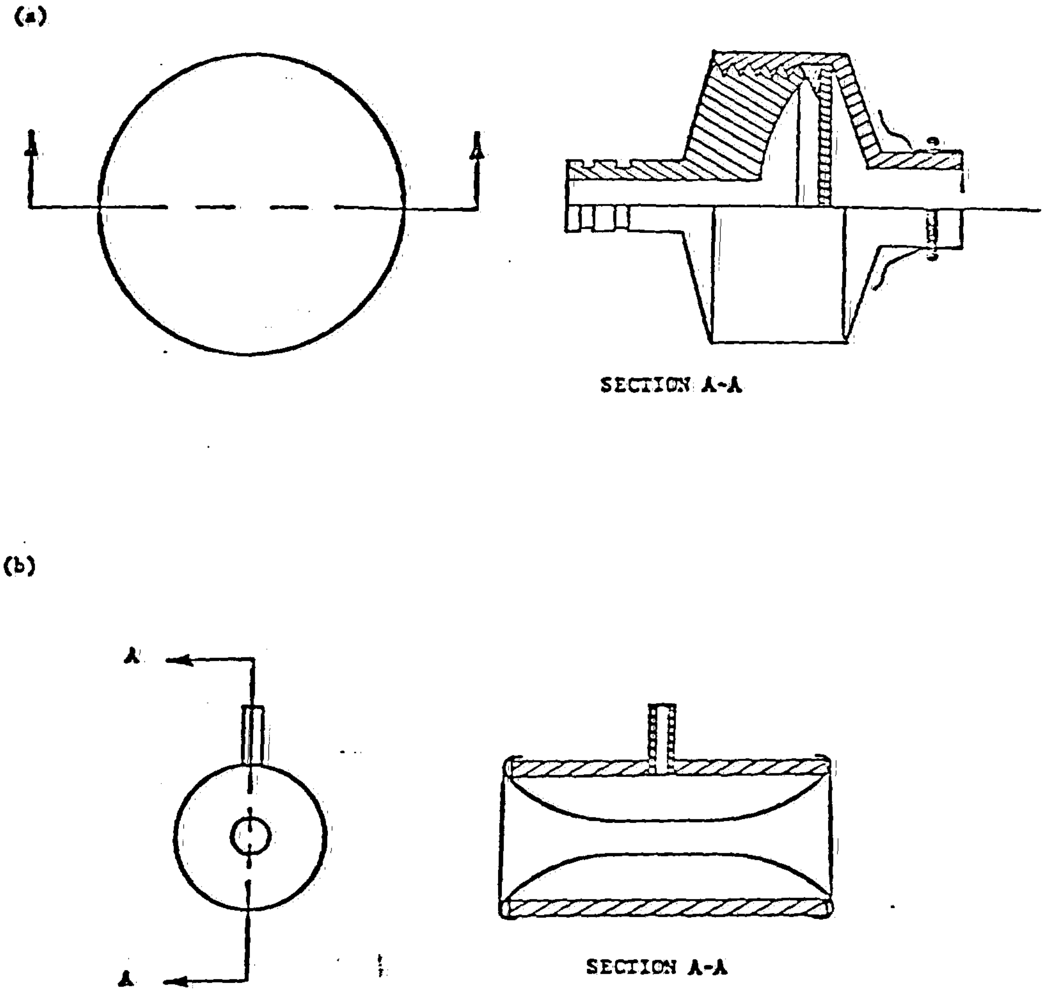

Figure A. The Three Filter-Holders Tested:
(a) Cambridge, (b) Borgwaldt, and
Filtrona.

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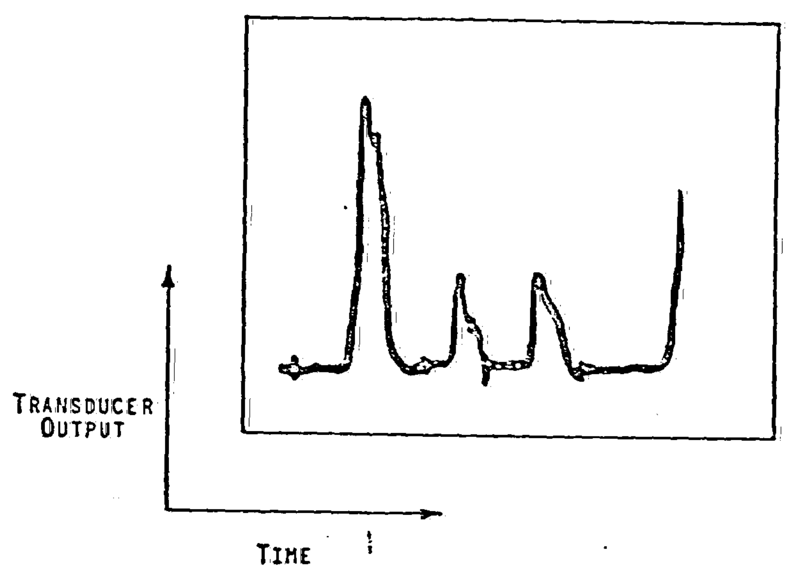

Figure 5. Oscilliscope Trace Showing The Voltage Output from the Pressure Transducer During Three Consecutive Puffs.

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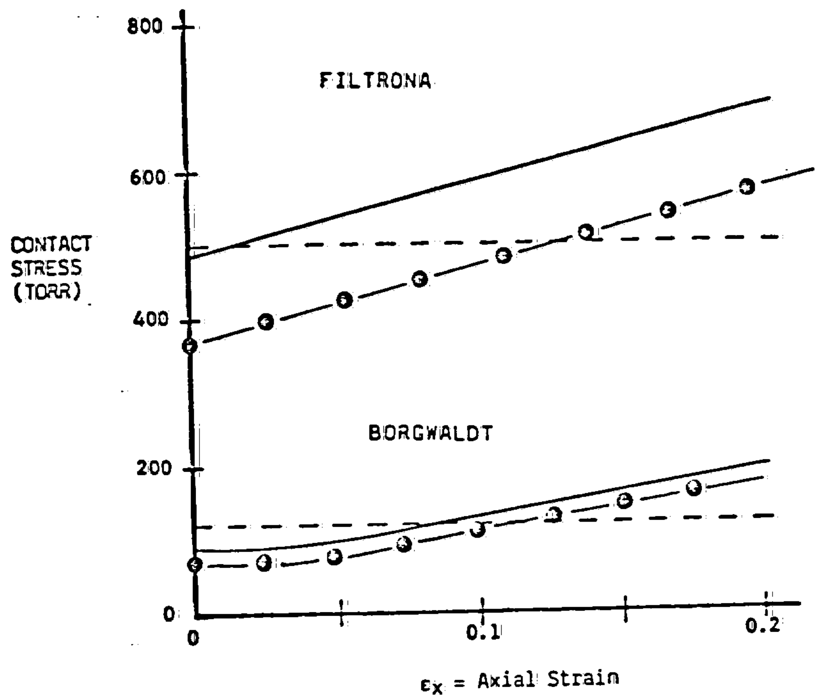

Small Deformation, Thin Wall Theory;

Large Deformation, Thick Wall Theory;

(ϵ_x = 0 only)

Measurements Using Miniature Sensing Probe.

Figure 6. Predicted values of contacted stress for the Filtrona and Borgwaldt holders as a function of applied axial strain.

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